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Dustin P. Graves

Kyle D. Moore

Anthony N. Palazotto
Air Force Institute of Technology

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Analysis of a Celestial Icosahedron Shaped Vacuum Lighter than Air Vehicle

Dustin P. Graves[a], Kyle D. Moore[a,*], Anthony N. Palazotto[a]

[a] *Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright Patterson AFB, OH 45433*

Abstract

The celestial icosahedron geometry is considered as a potential design for a vacuum lighter than air vehicle. The goal of this research is ultimately to determine the feasibility of the design and to understand the initial fluid-structure interaction of the vacuum lighter than air vehicle and the surrounding airflow. The aerodynamic effects of a deformed structure due to the external atmospheric pressure must be understood. In order to obtain a solid model to manufacture a structure for use in wind tunnel and computational fluid dynamics analysis, a method for converting structural analysis models into a physical representation had to be developed. The pressure profiles experienced by the structure in the wind tunnel experiments and computational fluid dynamics analysis are comparatively similar. Therefore, the computational fluid dynamics data is used to conduct a structural analysis in which aerodynamic effects are incorporated. The research concluded that the aerodynamic pressures do not significantly affect the stress on the structure at a wind velocity of 15.6 m/s and sea-level atmospheric conditions. As a result, it is recommended that the celestial structure be considered as a potential vacuum lighter than air vehicle design, and further nonlinear analysis be carried out for a final design.

Keywords: additive manufacturing; computational fluid dynamics; finite element analysis; lighter than air vehicles.

*Corresponding author.
E-mail address: kyle.moore.26@us.af.mil

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Nomenclature

ADA	Americans with Disabilities Act
AFIT	Air Force Institute of Technology
CAD	computer-aided design
CFD	computational fluid dynamics
CNT	carbon nanotube
FS	factor of safety
LTAV	lighter than air vehicle
UHM	ultra high modulus
VLTAV	vacuum lighter than air vehicle
VM	Von Mises
WSU	Wright State University
r_{beam}	beam radius
t_{beam}	beam thickness
t_{skin}	skin thickness
V_{frame}	volume of frame
V_i	internal volume
V_r	reduced volume
V_{skin}	volume of skin
W/B	weight-to-buoyancy
$\rho_{air,i}$	air density inside
$\rho_{air,o}$	air density outside
ρ_{frame}	density of frame material
ρ_{skin}	density of skin material

1. Introduction

Throughout history, humans have utilized lighter than air vehicles (LTAV) as a form of air travel. Many variations of LTAVs have been produced, ones which utilize different methods of obtaining a lighter than air gas within the membrane of structure. Methods used include heating the internal air of the LTAV as well as using lighter than air gases, to include hydrogen and helium. However, the prospect of utilizing sufficiently strong and light materials, while evacuating the air inside the body to create a vacuum, is becoming more realistic every year. A vacuum lighter than air vehicle (VLTAV), studied in this research, is a possible alternative to traditional LTAVs. Through research at the Air Force Institute of Technology (AFIT), three structural designs have emerged to solve the structural integrity problem for a VLTAV. The ideal shape to consider when minimizing a weight-to-buoyancy (W/B) ratio is a sphere. A sphere produces the most internal volume (vacuum) for the smallest surface area (structure, i.e. weight) and consequently the most lift ($W/B<1$ is necessary in order to achieve lift). However, a perfectly spherical shell would not be able to withstand the external atmospheric pressure if its thickness is reduced to a point where a $W/B<1$ is achieved. Therefore, in his thesis, Trent Metlen first introduced the idea of an icosahedron, a geodesic sphere that approximates a sphere using straight lines [1].

Next, Brian Cranston proposed, in his dissertation, the design of a hexakis icosahedron which would provide an even closer approximation to a sphere. Along with the hexakis, Cranston also proposed the celestial icosahedron structure, which provided the closest approximation of a sphere to date. It must be noted that in the event that the vehicle were to be optimized for aerodynamic purposes, the sphere-like shape may not be the optimal design.

Metlen's icosahedron was derived from a 1957 Buckminster Fuller patent for a geodesic dome [2]. The icosahedron is a polyhedron with 20 equilateral triangles in which the vertices lie on the surface of an imaginary sphere. To create an internal vacuum, a membrane must be draped over the icosahedron frame. The frame provides structural integrity for the LTAV, and the membrane provides a means to create the vacuum. Metlen's icosahedron, shown in Figure 1, was modeled for his analyses with an Ultra High Modulus (UHM) carbon fiber tube frame and a reinforced Mylar membrane draped over the frame [1].

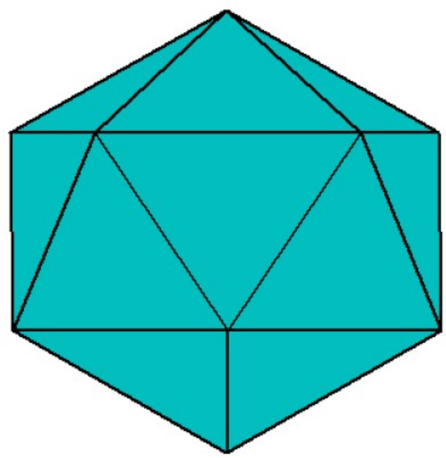

Figure 1: Metlen's Icosahedron [1]

Cranston's hexakis icosahedron came about due to the fact that Metlen's icosahedron holds a significantly smaller internal volume compared to a perfect sphere, especially when considering larger structural diameters. By increasing the diameter of the structure, the W/B ratio is reduced further compared to structures with smaller diameters. In certain applications, this volumetric void becomes problematic. As a result, Cranston proposed a structure even closer in shape and volume to a sphere, the hexakis icosahedron. The hexakis icosahedron, shown in Figure 2, has 120 faces and 62 vertices.

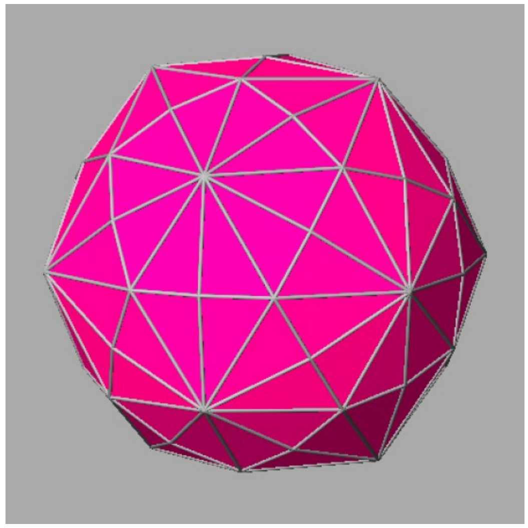

Figure 2: Cranston's hexakis icosahedron [3]

Finally, Cranston proposed the most spherical design to date, the celestial icosahedron. The celestial icosahedron design (Figure 3) consists of intersecting, circular rings as opposed to the straight rods found in the previously mentioned icosahedron and hexakis icosahedron. Instead of flat, connected triangular faces, the celestial icosahedron has nine intersecting rings revolved around each axis offset by 45 degrees. Cranston did not analyze the celestial icosahedron structure thoroughly, so this research studied the feasibility of the design, to include various diameters and materials used in previous feasibility studies.

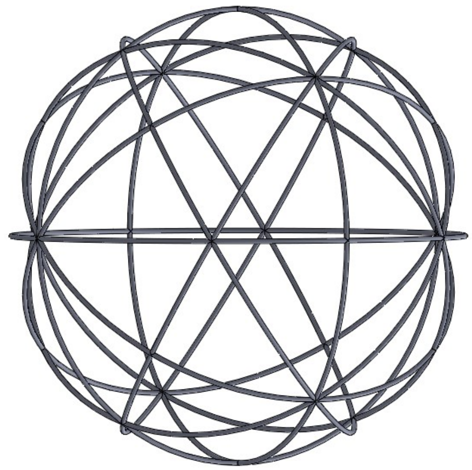

Figure 3: Celestial icosahedron frame in Solidworks

The icosahedron, hexakis icosahedron, and celestial icosahedron, each designed by previous researchers, have unique advantages as designs for a VLTAV. The celestial icosahedron provides the most similar geometry to a sphere, and therefore the most internal volume to be evacuated. An aspect of design analysis that has not been taken into account in past VLTAV research is the aerodynamic effects on the structures when deformed under an internal vacuum. Airflow around these shapes will cause pressures and other aerodynamic phenomenon not yet considered in the structural analyses of the VLTAVs. Consequently, the purpose of this research is to provide the initial aerodynamic analysis that can be utilized to determine if the fluid-structure interaction of a VLTAV is a problem worth further consideration. First, this research investigates the feasibility of the celestial icosahedron design as a VLTAV.

The next objective of this research is to determine whether the aerodynamic effects on the celestial icosahedron VLTAV with a structural diameter of 0.7576 m significantly affect the structural integrity of the VLTAV [3, 4]. Comparing the structural response to aerodynamic effects with the structural response of an internal vacuum at sea-level pressure provides insight into whether or not it is important to consider aerodynamic effects in future research of this vehicle. The pressures subjected to the structures as they resist freestream airflow can be utilized to update the structural analysis models. Until now, the research at AFIT has assumed symmetric sea-level pressure acting on the surface of the membrane for all of the structures. However, because this is a dynamic problem, the effects of airflow around the structure must be taken into consideration when structurally analyzing the VLTAVs. The final result of this study would determine if the structure considered is a candidate for further consideration knowing that there would be a great deal more work to be done for a final design.

2. Research Motivation

The motivation for this research includes determining the feasibility of the celestial icosahedron design as the optimal design to date. The celestial icosahedron is analyzed for three different structural diameters to determine the feasibility of the design. First, 1.2192 m, which corresponds to the smallest feasible diameter of the hexakis icosahedron from Schwemmer's work [5]. Next, a design based on a diameter that could be used in an urban surveillance environment (e.g. inside an office structure) was analyzed. A 0.8001 m diameter was chosen to conform to the minimum opening for a doorway according to the Americans with Disabilities Act (ADA), 0.8128 m [6]. Lastly, an analysis was conducted to determine the minimum diameter of a positively buoyant celestial icosahedron. The analyses conducted for these diameters are used to determine the feasibility of the celestial icosahedron, and to compare the design to the others previously investigated.

Another goal of this research is to determine if a full nonlinear fluid-structure interaction analysis is necessary when considering the celestial icosahedron as a VLTAV design. The initial stage of the fluid-structure interaction, as presented in this research, indicates whether a full analysis is necessary based on the stresses reported in the structural analysis with aerodynamic effects incorporated. In order to determine the aerodynamic effects, the second motivation for this research is realized. For wind tunnel and computational fluid dynamics (CFD) analyses to be possible, a physical representation of the results of the structural analysis of the celestial icosahedron with a simulated internal vacuum must be developed. Therefore, a method for creating a solid part based on the deformation results from a structural analysis had to be developed.

3. Methodology

The feasibility of the celestial icosahedron design as a VLTAV is determined through utilizing the finite element analysis software Abaqus. The acceptance criteria for determining the feasibility of each of the three celestial icosahedron diameters includes the factor of safety (FS) as well as the W/B ratio. If a model yields a FS$\geq$1.5 and a W/B<1, the design is considered feasible. For the 1.2192 m diameter model, the feasibility parameter for the FS was changed to 1.15 to correspond to the FS achieved by Schwemmer's optimized hexakis icosahedron. The material properties used for the analysis are consistent with the material properties associated with carbon nanotube (CNT) composites and Graphene for the frame of the structure and the membrane respectively. The material properties for CNT and Graphene are shown in Table 1 [5].

Table 1: Material properties used in analysis

Material	**Density (kg/m^3)**	**Poisson's Ratio**	**Young's Modulus (GPa)**	**Yield Stress (GPa)**
CNT	1250	0.33	293	3.8
Graphene	2000	0.10	500	50

The W/B ratio is determined by associating the buoyancy of an overall structure with the weight of its materials. In the case of the VLTAV, the ratio compares the weight of the structure (including any internal air) with the weight of the air that the structure displaces with its external volume. Eq. 1 shows this relationship [7].

$$(W/B) = \frac{V_{skin}\rho_{skin} + V_{frame}\rho_{frame} + (V_i - V_r)\rho_{air,i}}{(V_i - V_r)\rho_{air,o}} \tag{1}$$

For this research, the FS is calculated by taking the given materials yield stress (3.8 GPa for the frame, 50 GPa for the skin) and dividing that by the maximum Von Mises (VM) stress experienced by the respective structure during the analysis. The overall FS for the structure is then determined by taking the lower of the two FSs between the frame and the skin. Once the feasibility of the celestial icosahedron design is determined by these parameters, a physical model of the deformed shape must be built to determine aerodynamic effects on the structure.

The deformed mesh derived from the structural analysis conducted in Abaqus is exported as a point cloud file of nodal positions into the SolidWorks computer-aided design (CAD) software. The SolidWorks add-in, ScanTo3D, allows for the creation of a solid body structure by mapping surfaces onto the point cloud and adding a thickness to those surfaces. Once a solid body representation of the deformed structure is produced, SolidWorks is used to post process the geometry for use in wind tunnel testing.

Because the converged mesh, from a geometric standpoint, is relatively coarse (Figure 4), an interpolation function in MATLAB is used to smooth the contours of the point cloud file from Abaqus. The function interpolates nodal coordinates in a spherical coordinate system using natural neighbor interpolation methods. Figure 5 shows the result of applying the MATLAB interpolation function to the original point cloud file that was exported from Abaqus.

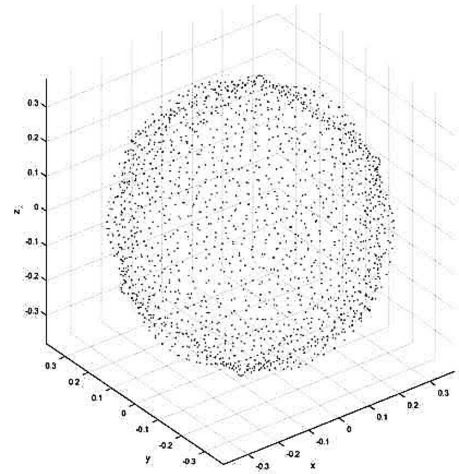

Figure 4: Nodal coordinates of structural analysis mesh prior to point cloud interpolation using MATLAB function

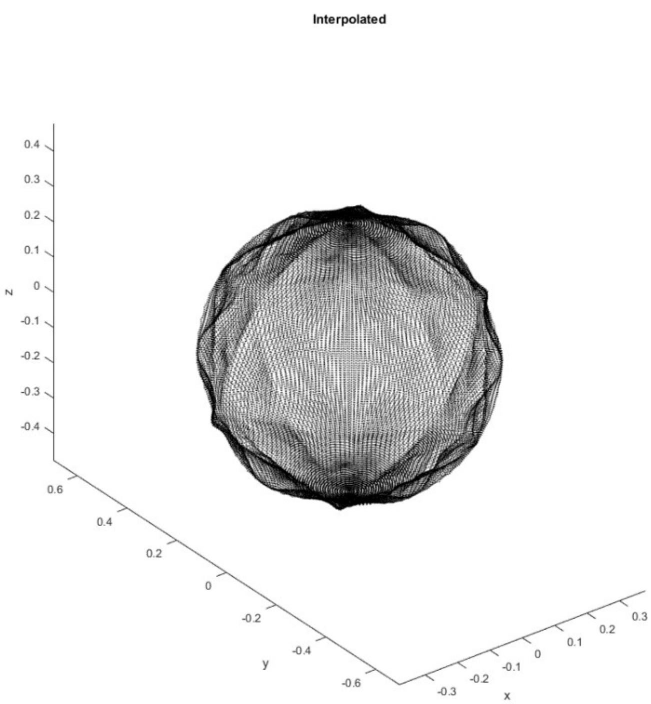

Figure 5: Result of applying point cloud interpolation, using MATLAB function, to the structural analysis mesh

Once the interpolation function provides finer resolution, the new point cloud is imported into the SolidWorks ScanTo3D add-in for conversion to a solid body. The Mesh Prep and Surface Wizards within the add-in add physical geometry to the point cloud file by draping surfaces over the x-y-z points within the point cloud. These surfaces can be thickened to create a solid body that can be utilized for printing a wind tunnel model or to conduct the CFD analysis that was carried out for this research. The finished product, after converting the deformed mesh from the structural analysis to a solid body shape, is shown in Figure 6.

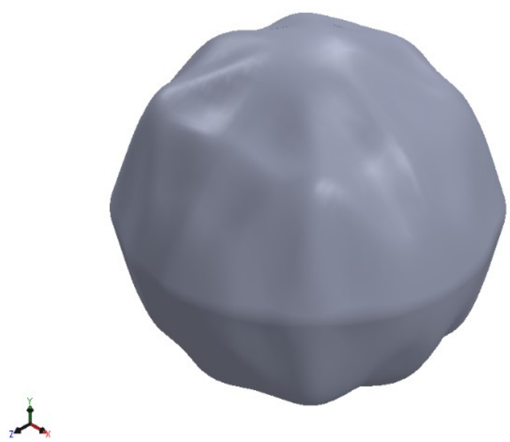

Figure 6: Deformed VLTAV post conversion from structural analysis mesh to solid body

In order to manufacture the test article, the solid body SolidWorks file is exported as an .STL file, which describes only the surface of an object through tessellation, and imported into Ultimaker Cura. The AFIT additive manufacturing facility's Ultimaker 3 printer was used to additively manufacture the wind tunnel test article and is shown in Figure 7. With a physical model, the aerodynamic data from wind tunnel experimentation can be compared to the data provided by the CFD analyses conducted in collaboration with Wright State University (WSU) [8]. The CFD model from WSU utilized the same .STL file described above. The experimental setup for the wind tunnel and the CFD mesh environment are compared in Figure 8.

Figure 7: Printing bottom of model in Ultimaker 3

CFD analysis provides better fidelity of the surface pressures on the deformed VLTAV for incorporation into the structural analysis software. The data from CFD can be used to create a custom pressure load within Abaqus to analyze the structure with aerodynamic pressures applied. The pressure applied to produce the results discussed in the next section are based on a wind velocity of approximately 15.6 m/s. This velocity was chosen, to a certain extent, based on a Congressional Budget Office report, Recent Development Efforts for Military Airships. The report states that "airships' difficulties in high winds generally constrain their operations to below 20,000 ft (6,096 m) and above 60,000 ft (18,288 m) because prevailing wind speeds tend to be greatest between those altitudes." The report also shows average wind speeds for Kabul, Afghanistan at approximately 25 knots (12.8 m/s) at 20,000 ft (6,096 m) and approximately 30 knots (15.4 m/s) at 60,000 ft (18,288 m) [9].

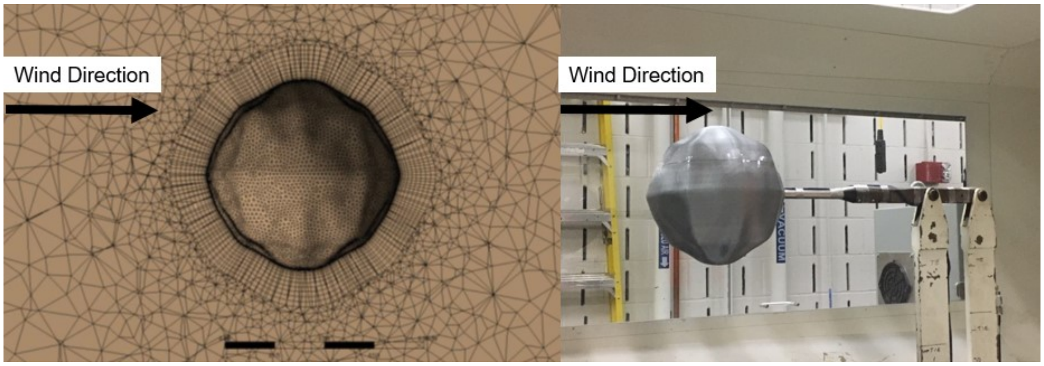

Figure 8: CFD and wind tunnel analysis setups

One of the goals of this research is to understand the fluid-structure interaction for a celestial icosahedron VLTAV. In order to understand this interaction, a method for incorporating the aerodynamic forces and pressures into the structural analysis had to be developed. The pressure is provided as a differential from atmospheric pressure. Therefore, the method for applying the differential pressure load from aerodynamic effects includes applying the load in a secondary step within the analysis after the atmospheric pressure has been applied to simulate the internal vacuum.

One of the products provided by WSU from its CFD analysis is a point cloud file of pressure distribution for each velocity at which the CFD model was run. The point cloud file provides an x, y, and z spatial location on the surface of the model with an associated pressure at that point. This pressure point cloud file is converted into a custom defined load within Abaqus for the structural analysis.

Within the Abaqus load module, the point cloud data is read in as an analytical mapped field. Analytical mapped fields allow for the addition of spatially varying load cases to a structural analysis. The Abaqus Online Documentation states that using analytical mapped fields, "you can define a spatially varying shell thickness or pressure load by providing the thickness or pressure values at different coordinates." The mention of applying spatially varying pressure values is exactly what this research looks to accomplish with the point cloud file exported from CFD [10].

4. Results and Discussion

4.1. Feasibility of the Celestial Icosahedron Design

Three different structural diameters were studied to evaluate the feasibility of the celestial icosahedron as a design for a VLTAV. The diameters included 0.8001 m which corresponds to the diameter that can fit through a door; 1.2192 m, which corresponds to Schwemmer's optimized diameter for the hexakis design; and finally a minimum diameter model, which attempts to determine the smallest diameter for the design, while maintaining a W/B<1.

The minimum W/B ratio achieved for the 0.8001 m structural diameter is 0.8994. The structure has a skin thickness of 7.85e-07 m with beam radii and thicknesses equal to 8.00e-03 and 2.00e-04 m respectively. The structure weighs 283.66 g, allowing a payload of up to 31.72 g. The FS for this structure is 1.50.

The minimum W/B ratio for a 1.2192 m structural diameter is 0.7257, compared to Schwemmer's 0.7654. The beam radius for the frame of the structure is 1.0925e-02 m; the corresponding beam thickness of the frame is 2.73125e-04 m. The skin thickness is 7.85e-07. The structure weighs 804.53 g with a maximum payload of 304.06 g. The FS for this structure was only 1.15 as discussed earlier to maintain consistency with Schwemmer's data for better comparison.

The smallest diameter feasible for the celestial icosahedron design was determined to be 0.7576 m. The feasible design had a skin thickness equal to 7.70e-07 m. The beam radii and thicknesses were 8.00e-03 m and 2.00e-04 m respectively. The weight of this structure was 268.37 g. This structure does not have the ability to carry a payload while maintaining positive buoyancy.

The results for each of the model diameters analyzed are tabulated in Table 2. These results show the overall feasibility of the celestial icosahedron as a design for a VLTAV. In the next section, the results of the structural analysis with aerodynamic effects are discussed.

Table 2: Summary of feasible designs

D (m)	0.8001	1.2192	0.7576
Frame Material	CNT	CNT	CNT
Skin Material	Graphene	Graphene	Graphene
r_{beam} (m)	8.00e-03	1.0925e-02	8.00e-03
t_{beam} (m)	2.00e-04	2.73125e-04	2.00e-04
t_{skin} (m)	7.85e-07	7.85e-07	7.70e-07
FS_{total}	1.50	1.15	1.50
W/B_{total}	0.8994	0.7257	0.9999
Payload (g)	31.72	304.06	0

4.2. Structural Analysis with Aerodynamic Effects

The pressure data reported by WSU is necessary to apply a load to the structural analysis. The structural diameter of the model that was analyzed is 0.7576 m; this corresponds to the minimum feasible diameter for the celestial icosahedron design. The CFD point cloud data provided by WSU supports higher fidelity in the pressure profile on the surface of the deformed VLTAV structure compared to the 16 data points collected during wind tunnel analysis. The higher fidelity provided by the CFD analysis is ideal for creating the pressure distribution on the surface of the membrane when conducting the structural analysis in Abaqus. Figure 9 indicates the results of the structural analysis with aerodynamic effects added for the 0.7576 m diameter celestial icosahedron VLTAV.

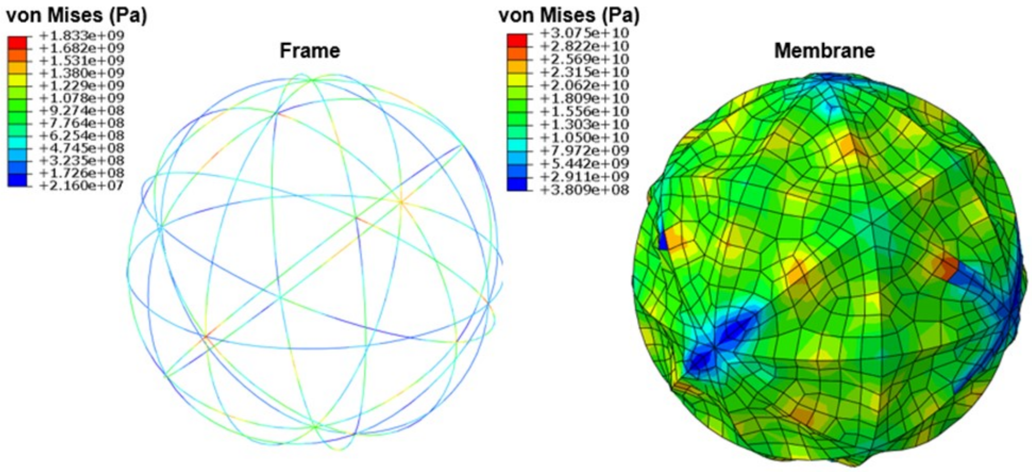

Figure 9: Maximum VM stress in the frame and membrane of the 0.7576 m diameter celestial icosahedron VLTAV with aerodynamic pressure added to symmetric sea level pressure

The results shown in Figure 9 are associated with a structural analysis conducted on the celestial icosahedron VLTAV with an added applied pressure profile representative of approximately 15.6 m/s flow. This is the highest equivalent velocity for which data was taken during wind tunnel analysis. The maximum VM stress experienced by the structure is 30.8 GPa and it is located within the membrane on the mid-points of the beams, between the ring connections. This is to be compared to the maximum VM stress, 33.4 GPa, of the structure only experiencing a symmetric pressure representative of sea level pressure. The relative location of the maximum VM stresses for both models were the same. Table 3 shows the comparison of the maximum VM stress in the frame and in the membrane with the material properties for CNT composite and graphene used for the frame and membrane respectively.

Table 3: Material properties compared to results from analysis of aerodynamic pressure added to symmetric sea level pressure (0.7576 m diameter, 15.6 m/s velocity)

Material	**Yield Stress (GPa)**	**Maximum VM Stress from Analysis (GPa)**	**Factor of Safety**
CNT (Frame)	3.8	1.8	2.1
Graphene (Skin)	50	30.8	1.6

The results from the structural analysis with aerodynamic effects applied shows that the FS for the frame and the membrane are greater than 1.5. The addition of the pressure profile from the CFD data does not significantly affect the maximum stress in the frame or membrane enough to reduce the FS below 1.5. In fact, compared to the analysis with only a symmetric sea level pressure applied to the outer skin, the addition of the pressure profile slightly increases the FS from 1.5 to 1.6. This is most likely due to the application of a pressure away from the center of the structure, at the point of maximum stress in the structure.

5. Conclusions

In this research, we conducted studies to determine if the three structural diameters for the celestial icosahedron design of a VLTAV were feasible. We also determined a method for manufacturing a physical model representative of the results of the structural finite element analysis. Lastly, we compared the FS of the structure subject to the airflow pressures, with the FS of the structure experiencing only a symmetric sea level pressure, which simulates an internal vacuum.

The 0.8001 m diameter model was produced to find the minimum W/B ratio possible for a model capable of fitting through an ADA approved doorway. The minimum W/B ratio achieved by this model was 0.8994, resulting in a maximum payload of 31.72 g. The total FS for the 0.8001 m diameter model was not affected by the skin thickness until the skin thickness was less than or equal to 8.00e-07 m. For skin thicknesses less than or equal to 8.00e-07 m, a linear relationship between the skin thickness and the total FS was observed; a smaller skin thickness resulted in a lower FS.

The 1.2192 m diameter model was produced in order to compare the celestial icosahedron's performance to the hexakis icosahedrons. Overall, the celestial icosahedron performed better than the hexakis icosahedron. For the same materials and FS, the celestial icosahedron is able to carry almost 100 g more in payload than the hexakis icosahedron.

Beam radii, along with the corresponding beam thickness, for the 1.2192 m diameter model were varied. For beam radii less than or equal to 1.09e-02 m, a proportional relationship was observed between the beam dimensions and the model's overall FS; smaller beam dimensions yield lower total FS. For beam radii greater than 1.09e-02 m, the maximum VM stress is contained in the skin.

The minimum diameter model was produced in order to determine the smallest possible diameter of the celestial icosahedron VLTAV, while maintaining positive buoyancy with no payload. The minimum diameter obtained was 0.7576 m and showed very similar FS and W/B ratio trends as the previous two models. In general, the diameter of the structure and the model's total FS were linearly proportional; a smaller diameter resulted in a larger FS. For changes in diameter less than 0.008 m, though, the total FS corresponding to a given skin thickness is unchanged. Similar to the 0.8001 m diameter model, larger skin thicknesses on the minimum diameter model resulted in a higher FS for the entire structure.

After analyzing the pressure profile as a load within the structural analysis model, the results showed that the structural integrity of the 0.7576 m diameter celestial icosahedron VLTAV was not significantly affected. For the atmospheric conditions considered in this research, the structural analysis indicates that the VLTAV does not experience high enough stresses in order to be at risk of collapse. Therefore, it is concluded that a full nonlinear fluid-structure interaction analysis is not necessary for the celestial icosahedron design at the conditions studied in this research. An initial evaluation of wind loading on a VLTAV was completed. The results verified by the wind tunnel experiment and characterized by CFD and finite element analysis indicate that an excessive stress situation does not occur. The approach described in this article is a first step in characterizing a nonlinear fluid-structure interaction which was not carried out further. The study was based on a steady state wind loading on one side of the structure. A symmetrical loading condition was initially evaluated on the model at sea level conditions, and this wind tunnel approach gave the quasi-static effect on an asymmetric loading. It is be lived that this approach is sufficient to represent the primary features of this new structure. For the final design, a great deal of work must still be done in order to evaluate many of the nonlinear characteristics related to the design, such as collapse, aerodynamics, and structural dynamics, but the authors were convinced that this structure is a good candidate for further evaluation as a VLTAV.

Conflict of interest statement

There is no conflict of interest.

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